VUV and X-ray Free-Electron Lasers

High-brightness Beam Techniques

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Tuesday Schedule

• High-brightness beam techniques	09:00 – 10:00
• Break	10:00 – 10:10
• Injector beam dynamics	10:10 – 11:10
• Break	11:10 – 11:20
• Bunch compression, laser heater & CSR	11:20 – 12:00
• Lunch Break	12:00 – 13:30
• Electron beam properties and FODO	13:30 – 15:15
• Break	15:15 – 15:30
• FEL simulations with Genesis	15:30 – 17:30

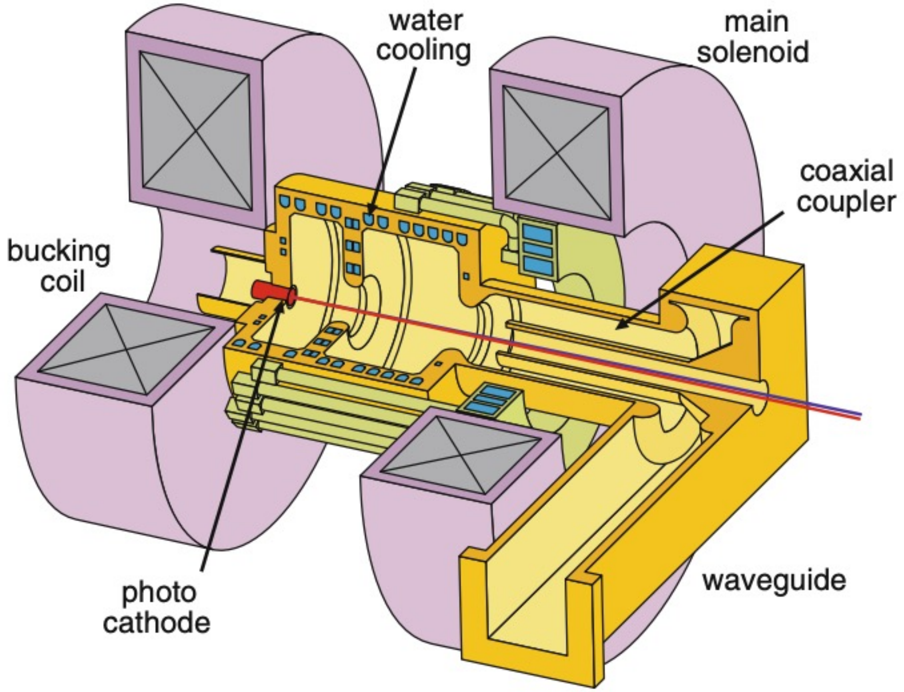
High-brightness Beam Techniques (Photoinjector Designs)

Overview:

Overview of Injector System

Cathode Types
- Photocathode vs. thermionic
- Photoemission
- Popular photocathode materials, QE

Operating Photoinjector designs
- High/low frequency
- Examples in facilities

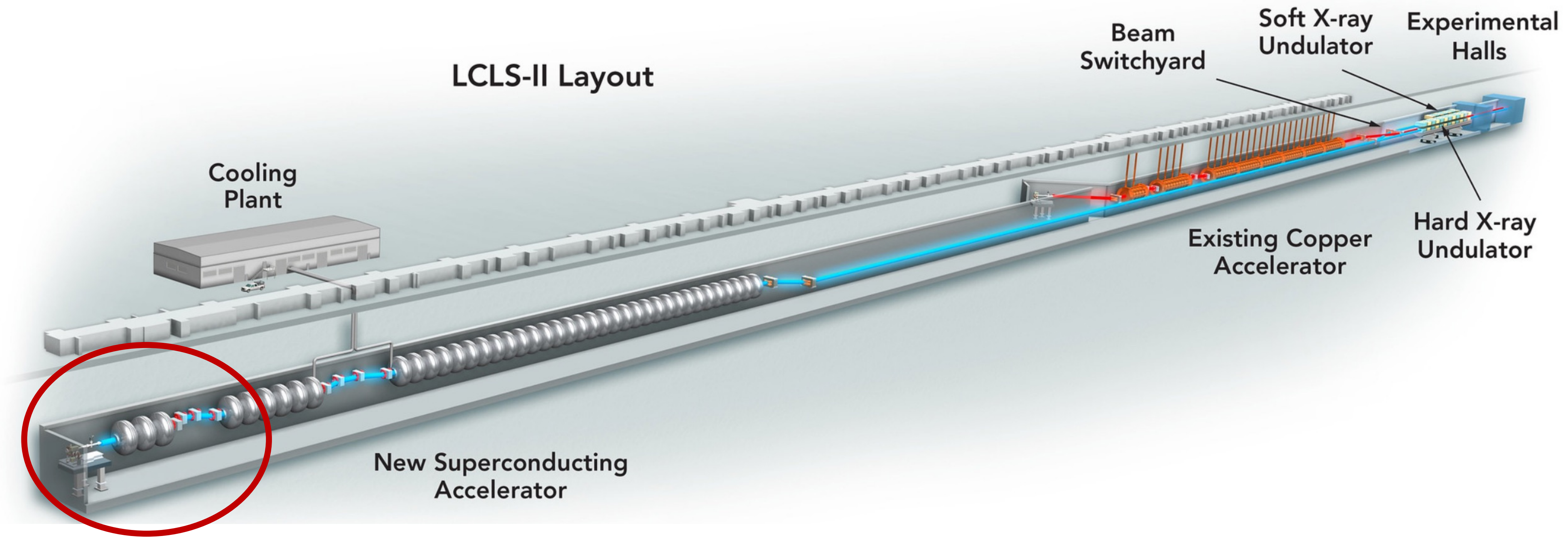


Pg. 136, text.

Overview of Photoinjector System

Motivation: Free Electron Lasers (FEL)

- RF/DC photocathode gun, e- usually the speed of light after the gun
- Commonly use copper or superconducting accelerating cavities
- Photoinjector & linac based light source

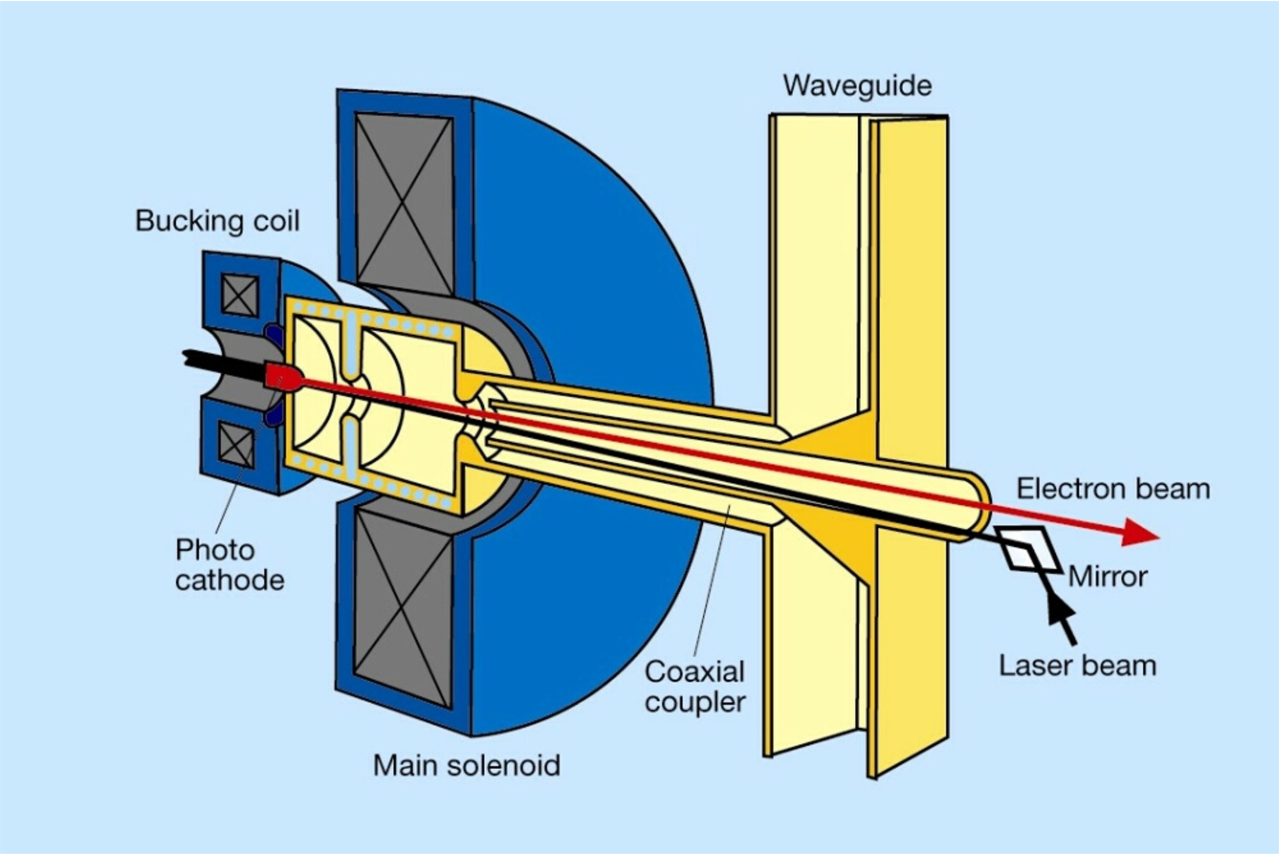


Picture source: SLAC flickr

Photoinjector Layout

At the beginning of any accelerator, a few key parts are needed:

- **Vacuum** - strict for electron machines w/ semiconductors
- **Photocathode** - source of particles
- **Laser** – To induce photoemission
- **Focusing** - solenoid magnets
- **Accelerating field –** Buncher/booster or accelerating cavity

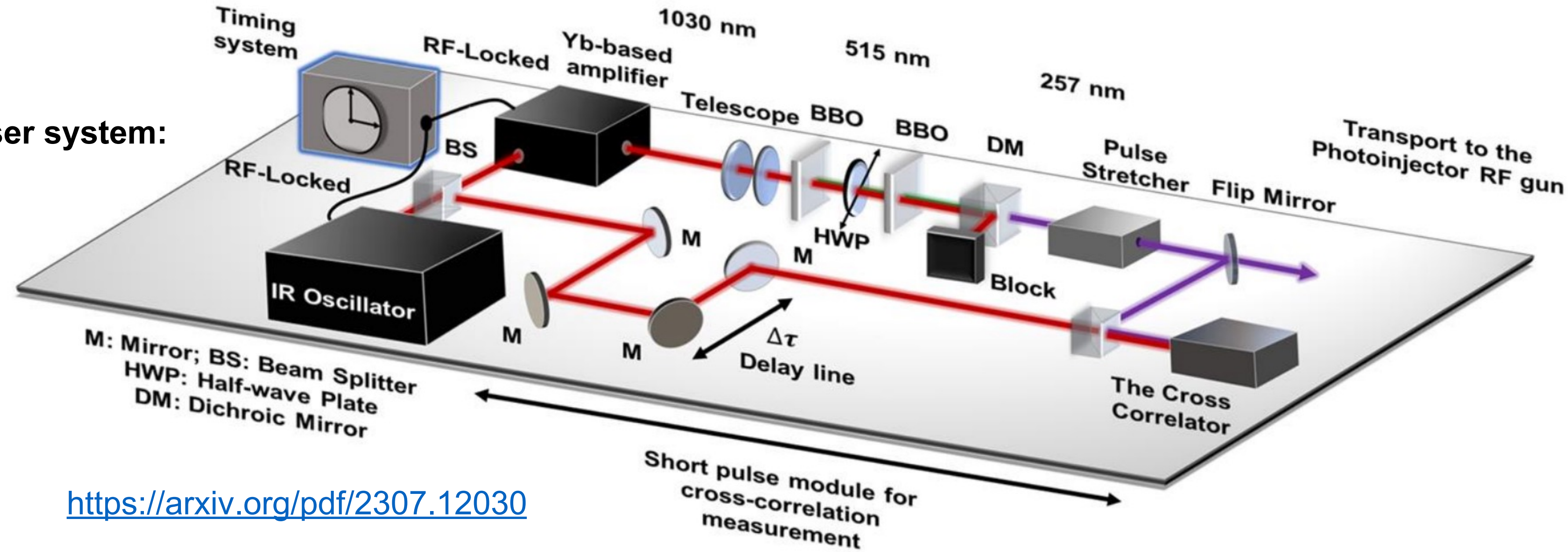


Source: DESY

Laser systems

- Required for photoemission on the cathode.
- Set the boundaries for beam initial conditions.
- Typically, IR to UV for semiconductor cathodes.
- Timing must be aligned with RF phases in the gun.
- Alignment into the gun can be problematic depending on the focusing & distance.

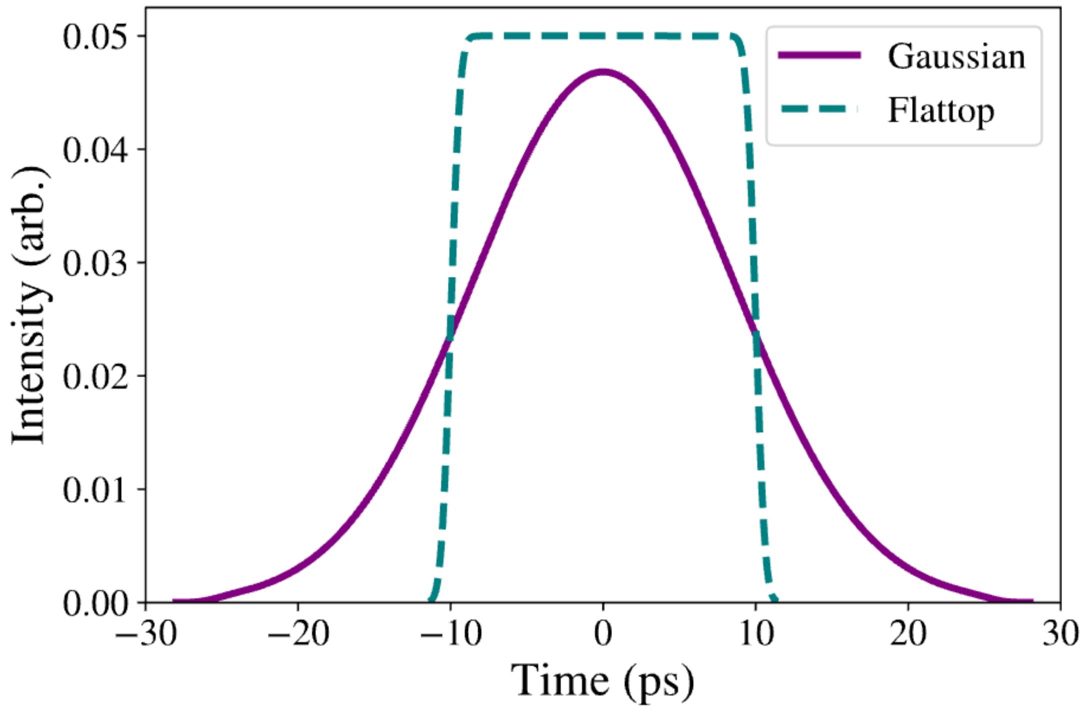
LCLS-II laser system:

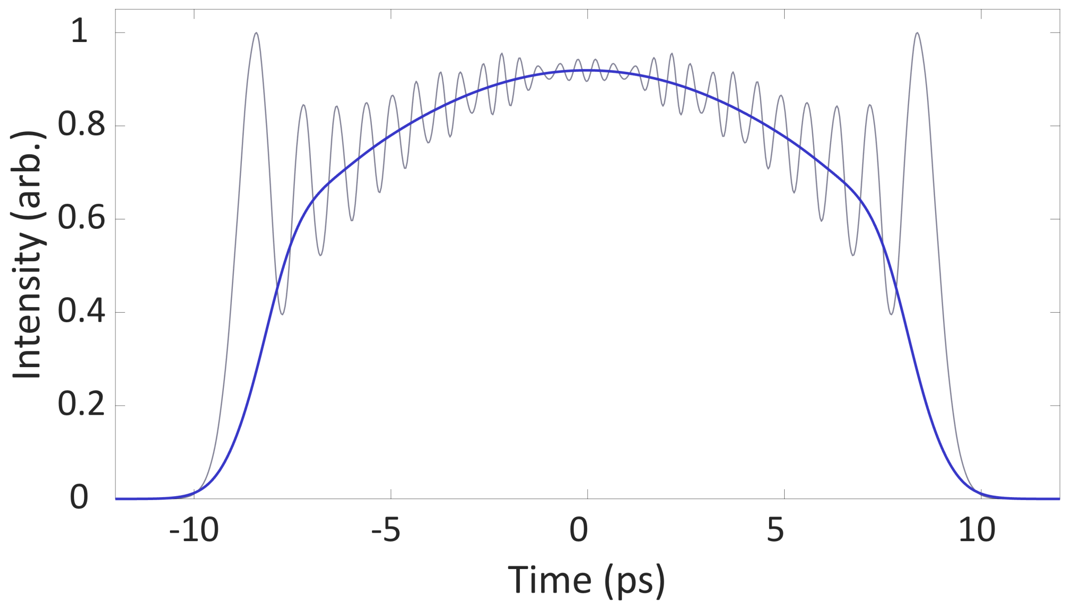


https://arxiv.org/pdf/2307.12030

Laser profiles: Longitudinal

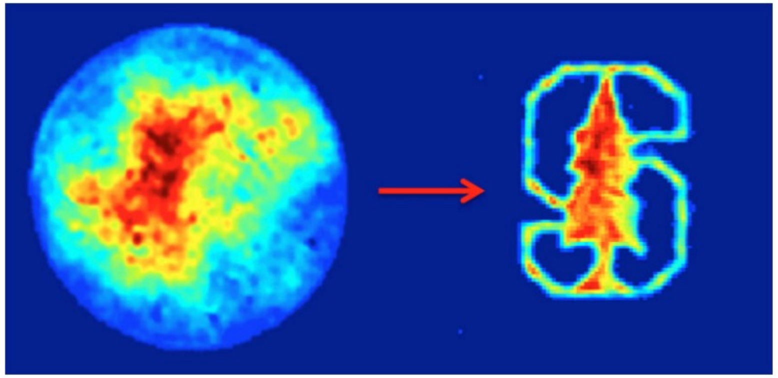
- Ideal simulated profile is often a flattop.
- At high repetition rates, this has not been achieved.
  - Laser technology limitations.
- Facilities typically use a Gaussian.
- Flattop-like profiles are being investigated (UCLA+).

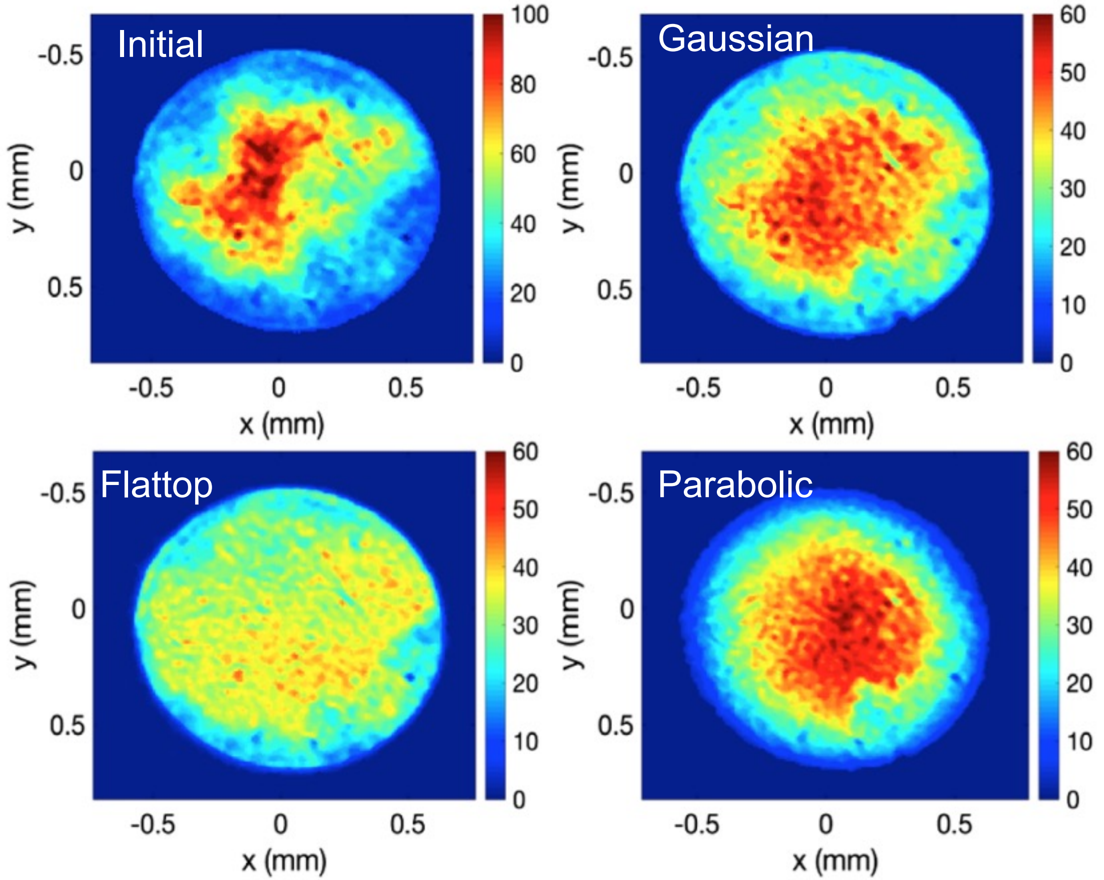




Laser profiles: Transverse

- Can be adjusted with focusing or irises.
- Must be adjusted to compensate for space charge.
  - Larger radius needed for larger charges.
  - Details on the math in the next talk…
- Typically, facility profile is not the ideal gaussian we simulate…
- Limited shaping success/demonstrations.



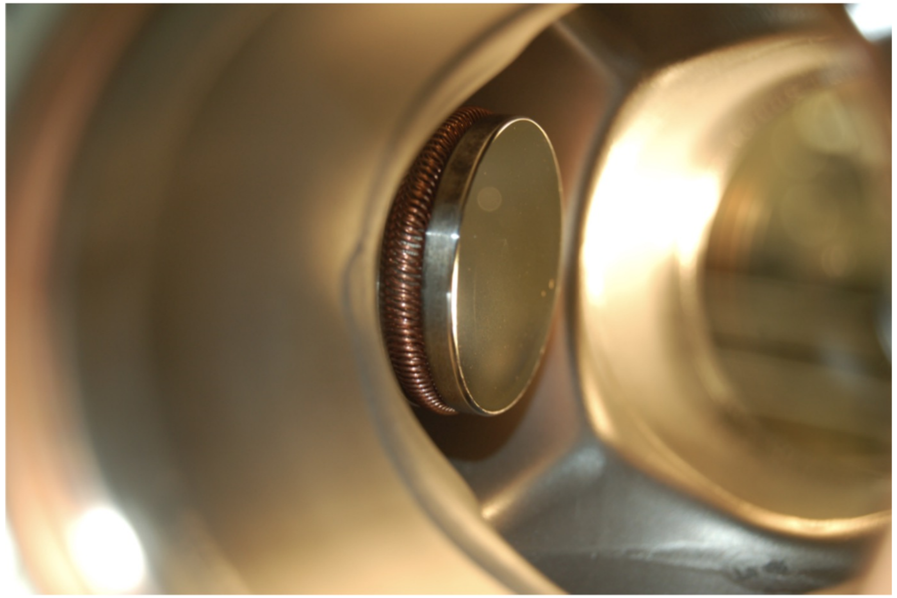


https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.20.080704

Photocathodes

Particles must come from somewhere…

- Gas
- Filament
- **Metals and semiconductors**



Source: AWA-ANL

Quantum efficiency and work function determine best materials:

- Cs_2Te, Mg, Cu
- Semiconductors used for material properties; surface grown in lab.

Accelerating Structures

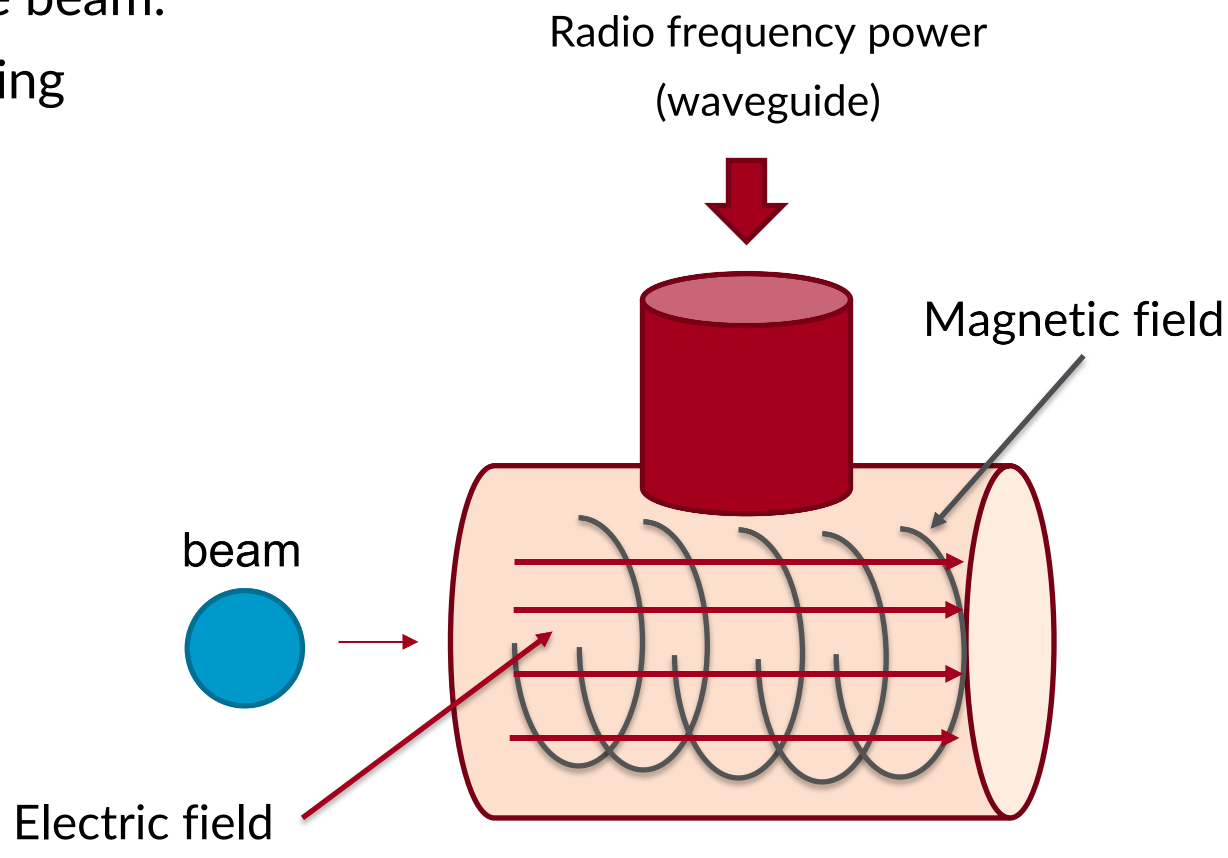
- Used to give additional energy to the beam.
- RF gun is a specific type of accelerating structure (with cathode).

Lorentz force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$\vec{E} = \vec{E}(r,t)\hat{z}$$

$$E_z = E(r)e^{i\omega t}$$

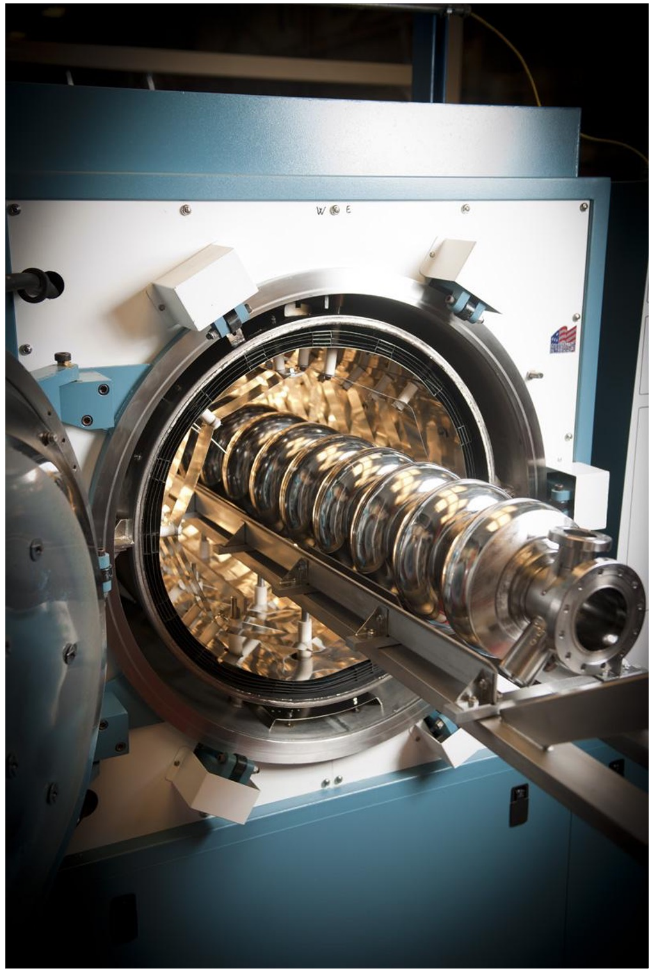


Accelerating Structures Examples: SLAC

The structures that follow the source / gun:

- Copper or superconducting (niobium).
- Used to give the particles more energy.
- Gradient is dominated by choice of material and geometry.

Source: SLAC flickr



Source: Fermilab

Discussion

- Why are FEL's laid out the way they are? Why are they so long?
- Does the laser repetition rate limit the beam rate?
  - What does the laser profile impact?
- What factors limit the accelerating gradient?
  - How does this impact the FEL?

Cathode Types

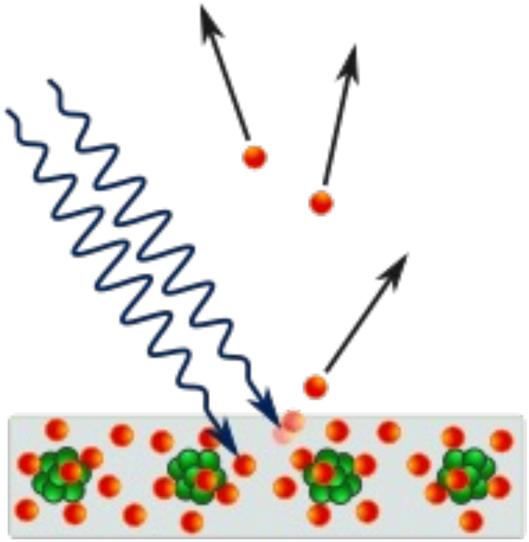
Cathode Types

Photoemission

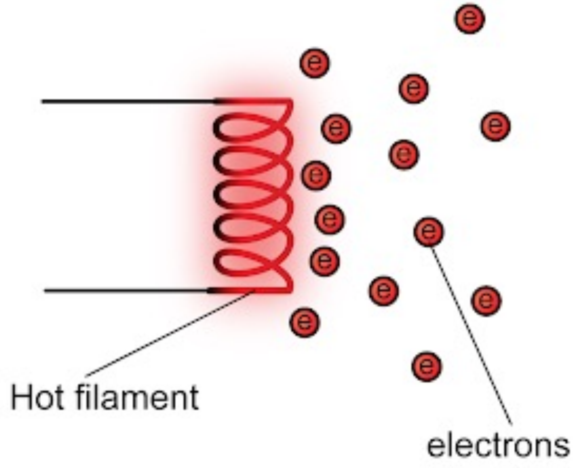
- Electrons are generated via the photoelectric effect
- The laser pulse heavily impacts the initial bunch shape (emittance & space charge)
- High electron brightness
    - i.e. reduced emittance
- Brightness ~ 10^{15} A/(m-rad)^2

Thermionic Emission

- Not the focus for this class/FELS…
- Longer bunch lengths, less control, larger emittances
- Brightness < 8 x 10^8 A/(m-rad)^2



https://en.wikipedia.org/wiki/Photoelectric_effect

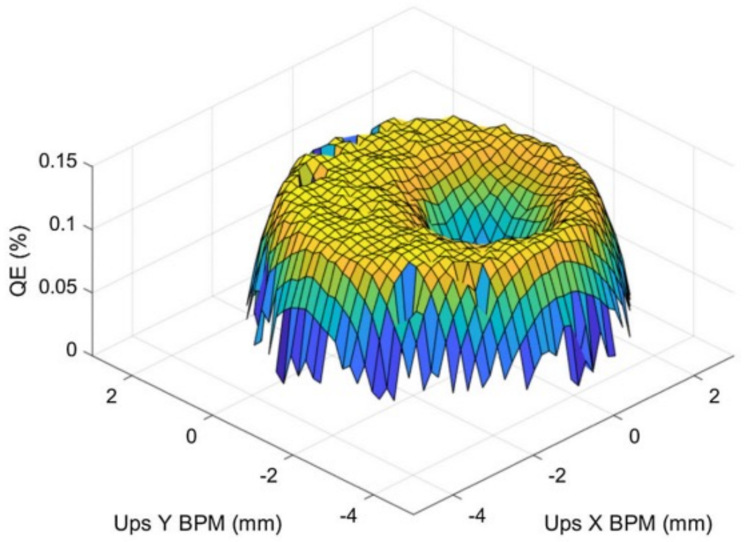


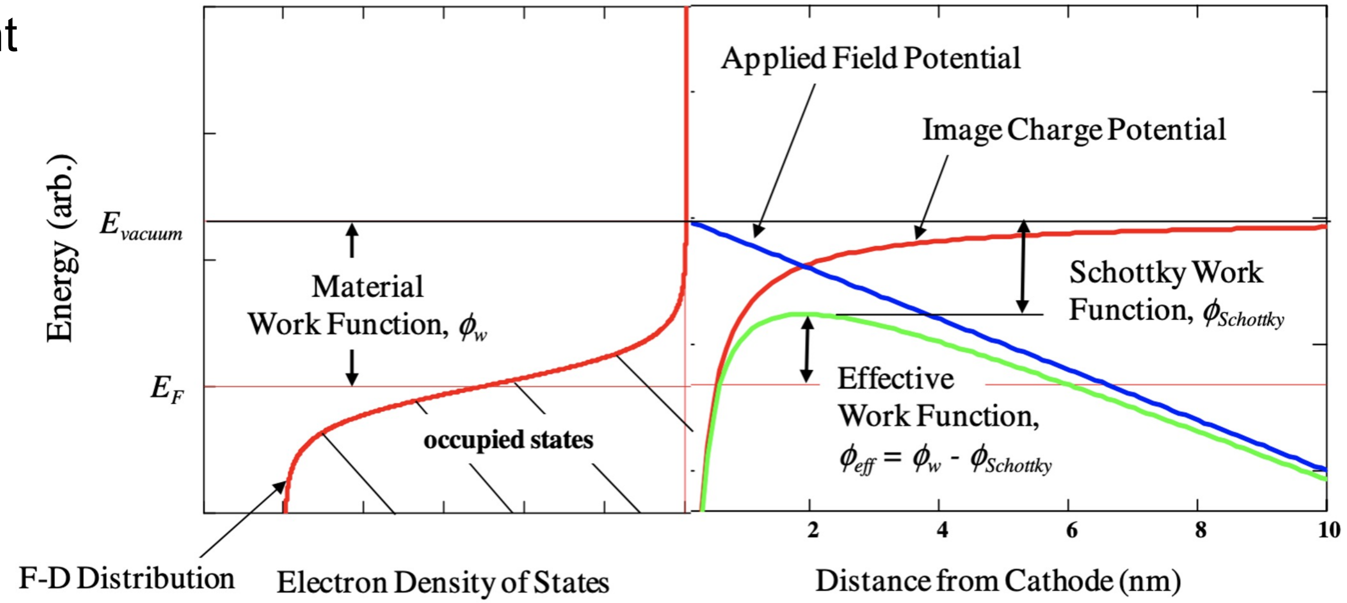
https://spmphysics.blog.onlinetuition.com.my/electronic/thermionic-emission/

Photocathodes: Quantum Efficiency

- **Quantum efficiency** = ratio of photoelectrons to incident photons
- **Work function** = energy needed to remove an unbounded electron
- **Schottky effect** = reduction in work function when strong external electric field is present

$$QE[\%] = \frac{N_{electrons}}{N_{photons}} = \frac{\hbar c}{e}\frac{I[A]}{P[W]\lambda[\mu m]}$$





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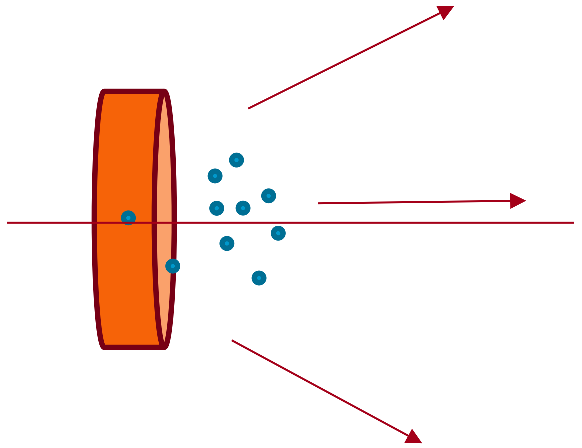
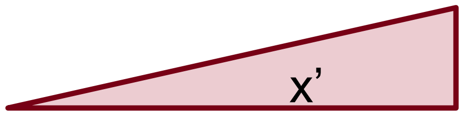
Emittance

Photocathode

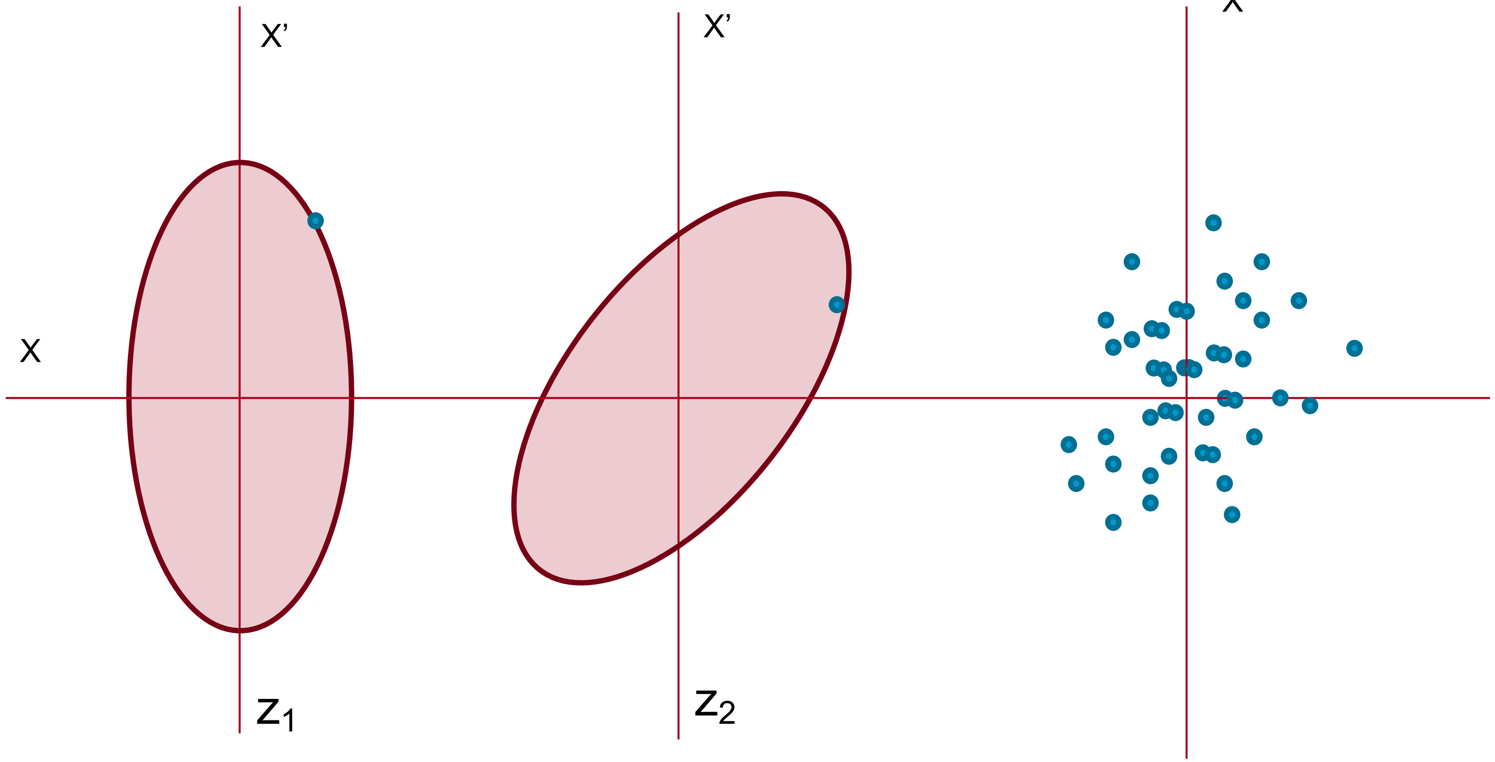


$$\varepsilon = \sqrt{\langle x^2 \rangle \langle {p_x}^2 \rangle - \langle x p_x \rangle^2}$$

$$\varepsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$



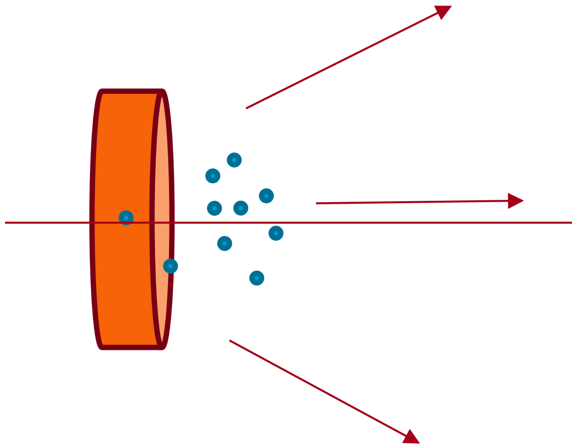
Phase space:



Note: x' is an angle, not pure momentum

Thermal Emittance

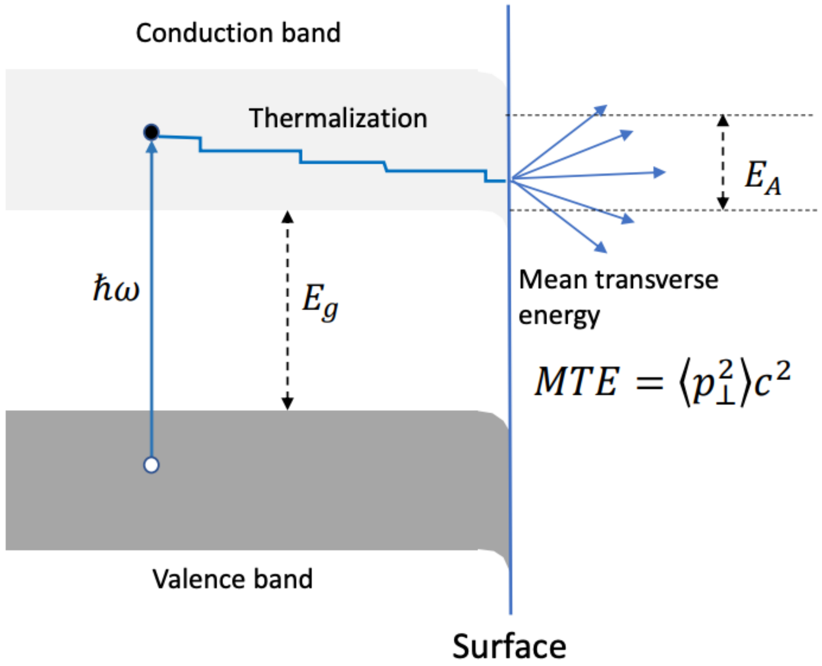
Photocathode



- Transverse momentum of emitted electrons.
- Depends on photocathode material.
- Sets the lower bound on emittance.
- Sets upper bound on brightness achievable.

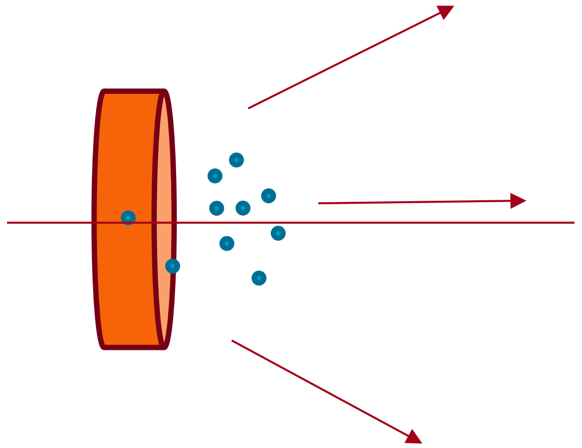
$$\varepsilon_{nx,thermal} = \sigma_x \sqrt{\frac{MTE}{m_e c^2}}$$

m_e = electron mass
c = speed of light
σ_x = beam size
MTE = mean transverse energy



Other sources of Emittance

Photocathode



$$\varepsilon_{total} = \sqrt{\varepsilon_{th} + \varepsilon_{rf} + \varepsilon_{sc} + \varepsilon_B}$$

ε_{th} = thermal
ε_{rf} = rf induced
ε_{sc} = space charge
ε_B = magnetic field

Intrinsic (thermal) emittance
- Photocathode material/work function
- Laser energy
- MTE

RF induced emittance
- Accelerating gradient
- Bunch length
- Electron phase

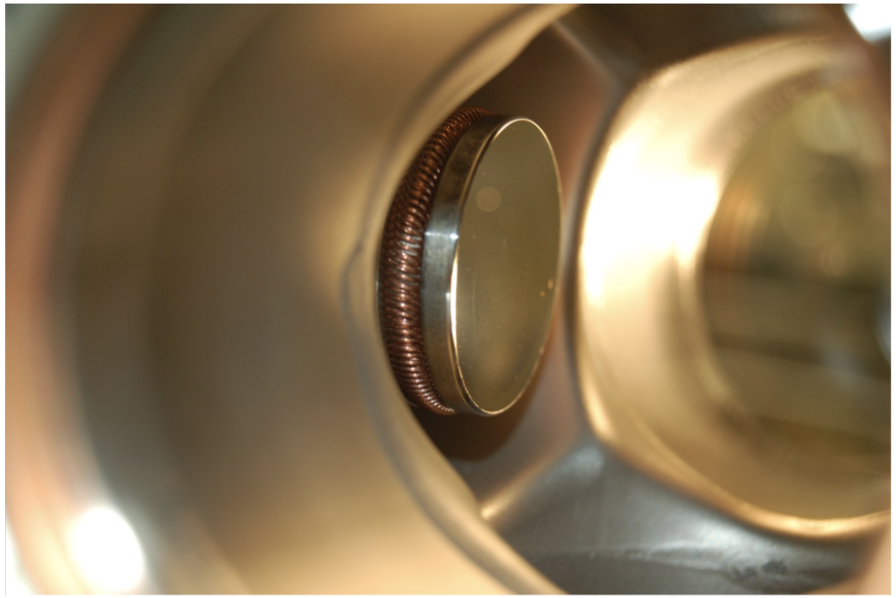
Space charge emittance
- Beam energy
- Charge (peak current)
- Solenoid compensation
- Transverse & longitudinal dimensions

Angular momentum
- Magnetic field at the cathode
- Transverse laser profile

Photocathodes: Materials

- The two main camps are metals and semiconductors.
- Common materials are Cu, Mg, Cs_2Te.
- Semiconductors are favored for the lower work function,

i.e. lower laser energy needed for similar amount of charge.

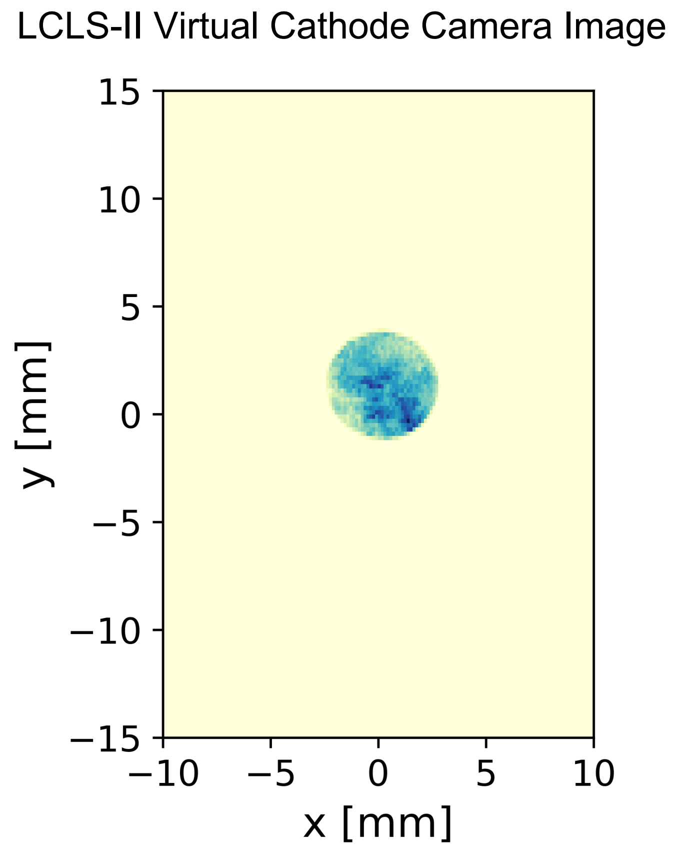


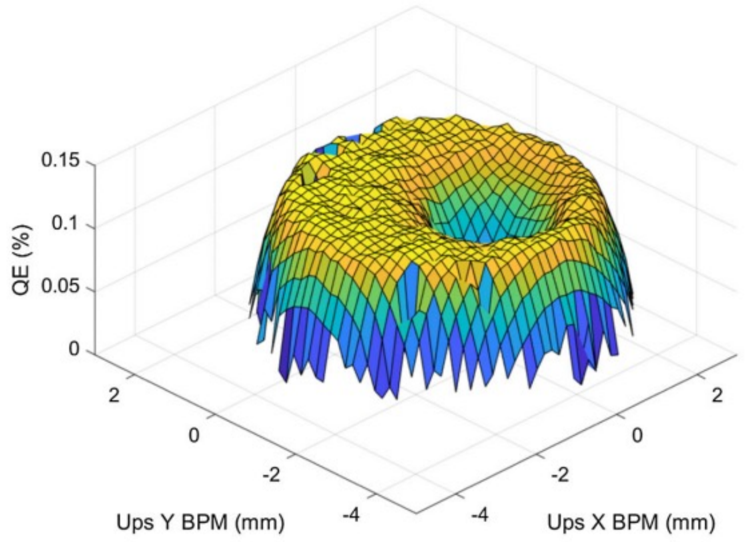
Source: AWA-ANL

	Cu	Mg	Cs_2Te	Unit
$\hbar\omega$	4.9	4.7	4.7	eV
ϕ or $(E_g + E_A)$	4.4	3.6	3.9	eV
MTE	167	367	250	meV
$\frac{\varepsilon_{T,n}}{\sigma_x}$ calculated	0.4	0.8	0.7	um/mm
min. measured	0.7	0.4	0.6	um/mm

Discussion

- Where do the particles come from?
- What are the advantages/disadvantages of photocathodes vs. thermionic?
- Why are certain cathode materials chosen?
- How does the QE change over time? Why?
  - How can this impact FEL performance?





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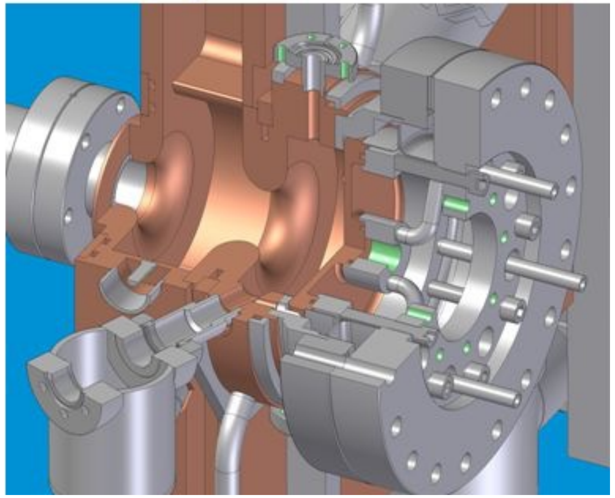
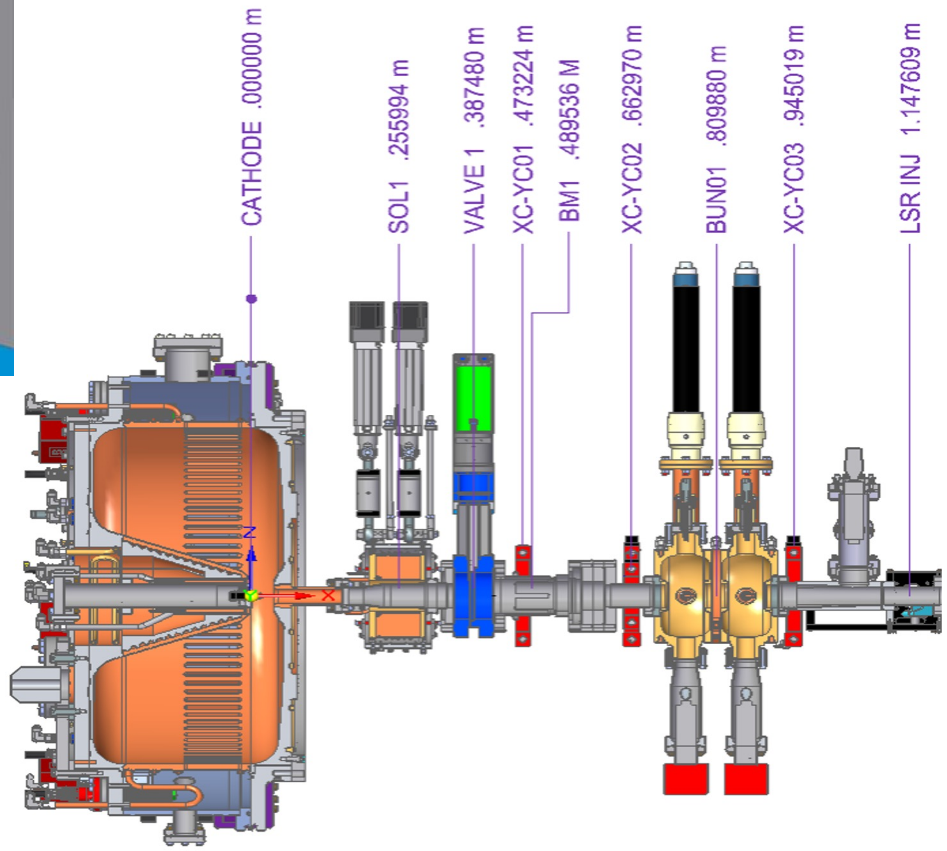
Operating Photoinjector Designs

Photoinjector Examples: SLAC

Cut-away view of LCLS Gun



Source: D. Dowell



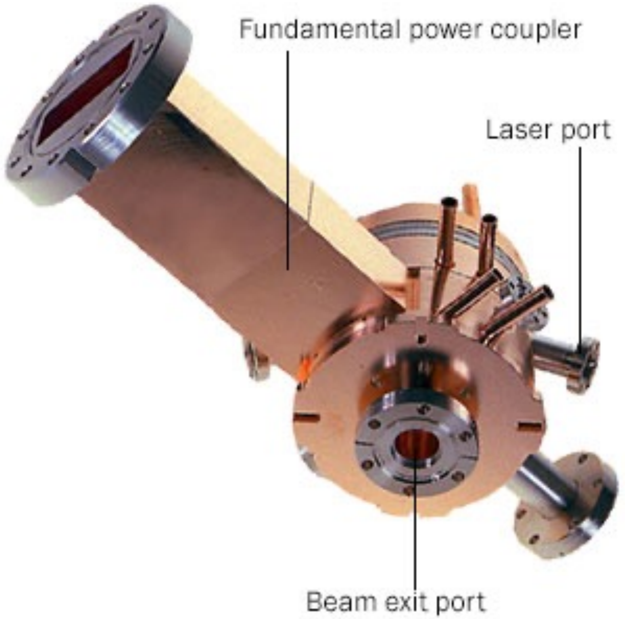
Linac Coherent Light Source (LCLS):

- 2.8 GHz, 1.5 cell, copper gun
- Repetition rate 120 Hz
- Gradient 120 MV/m
- Copper cathode
- 100-250 pC

LCLS-II gun

- 187 MHz quarter cell, copper gun
- Repetition rate 1MHz
- 1.3 GHz two cell buncher
- Gradient 20 MV/m
- CsTe cathode
- 20-100pC

Photoinjector Examples: ANL/BNL



https://www.bnl.gov/atf/beamlines/photoinjector.php

Accelerator Wakefield Accelerator Facility:

- Operates at 1.3 GHz
- 1.5 cell, copper cavity
- Repetition rate of 1-10 Hz
- CsTe cathode
- **1-100** nC charge

BNL Accelerator Test Facility:

- Operates at 2.586 GHz
- 1.6 cell, copper cavity
- Repetition rate of 1-10 Hz
- Copper cathode
- 0.1-1 nC charge

Summary

- Photoinjectors are used as the start of FELs.
- They consist of a laser system, photocathode, focusing elements, and accelerating cavities (gun).
- The emittance resulting from photocathode and injector parameters sets the upper limit on achievable brightness in an FEL.
- Common photoinjector gun designs include 1.5/1.6 cell guns, and quarter wave DC-like guns.